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## **Comparing Jupiter interior structure models to Juno gravity measurements and the role of a dilute core**

Wahl, S M ; Hubbard, W B ; Militzer, B ; Guillot, T ; Miguel, Y ; Movshovitz, N ; Kaspi, Y ; Helled, R  
; Reese, D ; Galanti, E ; Levin, S ; Connerney, J E ; Bolton, S J

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Comparing Jupiter interior structure models to *Juno* gravity measurements and the role of a dilute core

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**Abstract** The *Juno* spacecraft has measured Jupiter's low-order, even gravitational moments,  $J_2 - J_8$ , to an unprecedented precision, providing important constraints on the density profile and core mass of the planet. Here we report on a selection of interior models based on ab initio computer simulations of hydrogen-helium mixtures. We demonstrate that a dilute core, expanded to a significant fraction of the planet's radius, is helpful in reconciling the calculated  $J_n$  with *Juno*'s observations. Although model predictions are strongly affected by the chosen equation of state, the prediction of an enrichment of  $Z$  in the deep, metallic envelope over that in the shallow, molecular envelope holds. We estimate Jupiter's core to contain a 7–25 Earth mass of heavy elements. We discuss the current difficulties in reconciling measured  $J_n$  with the equations of state and with theory for formation and evolution of the planet.

**Plain Language Summary** The *Juno* spacecraft has measured Jupiter's gravity to unprecedented precision. We present models of the planet's interior structure, which treat the hydrogen-helium mixture using computer simulations of the material. We demonstrate that dilute core, with the heavy elements dissolved in hydrogen and expanded outward through a portion of the planet, may be helpful for explaining *Juno*'s measurements.

## 1. Introduction

The *Juno* spacecraft entered an orbit around Jupiter in July of 2016 and since then has measured Jupiter's gravitational field to high precision [Bolton et al., 2017]. Here we present a preliminary suite of interior structure models for comparison with the low-order gravitational moments ( $J_2$ ,  $J_4$ ,  $J_6$ , and  $J_8$ ) measured by *Juno* during its first two perijoves [Folkner et al., 2017].

A well-constrained interior structure is a primary means of testing models for the formation of the giant planets. The abundance and distribution of elements heavier than helium (subsequently referred to as "heavy elements") in the planet is key in relating gravity measurements to formation processes. In the canonical model for the formation of Jupiter, a dense core composed  $\sim 10 M_\oplus$  (Earth masses) of rocky and icy material forms first, followed by a period of rapid runaway accretion of nebular gas [Mizuno et al., 1978; Bodenheimer and Pollack, 1986; Pollack et al., 1996]. Recent formation models suggest that even in the core accretion scenario, the core can be small ( $\sim 2 M_\oplus$ ) or be diffused with the envelope [Venturini et al., 2016; Lozovsky et al., 2017]. If Jupiter is formed by gravitational instability, i.e., the collapse of a region of the disk under self-gravity [Boss, 1997], there is no requirement for a core, although a core could still form at a later stage [Helled et al., 2014]. Even if the planet initially formed with a distinct rock-ice core, at high pressures and temperatures, these core materials become soluble in liquid metallic hydrogen [Stevenson, 1985; Wilson and Militzer, 2012a, 2012b; Wahl et al., 2013; Gonzalez-Cataldo et al., 2014]. As a result, the core will erode and the heavy material

will be redistributed outward to some extent. In this study we consider the effect of such a dilute core, in which the heavy elements have expanded to a significant fraction of Jupiter's radius.

Significant progress has been made in understanding hydrogen-helium mixtures at planetary conditions [Saumon *et al.*, 1995; Saumon and Guillot, 2004; Vorberger *et al.*, 2007; Militzer *et al.*, 2008; Fortney and Nettelmann, 2010; Nettelmann *et al.*, 2012; Militzer, 2013; Becker *et al.*, 2013; Militzer *et al.*, 2016], but interior model predictions are still sensitive to the hydrogen-helium equation of state used [Hubbard and Militzer, 2016; Miguel *et al.*, 2016]. In section 2.1 we describe the derivation of barotropes from a hydrogen-helium equation of state based on ab initio materials simulations [Militzer, 2013; Hubbard and Militzer, 2016], make comparisons to other equations of states, and consider simple perturbations to better understand their effect on the models. In section 2.2 we describe details of these models including a predicted layer of ongoing helium rain out [Stevenson and Salpeter, 1977a, 1977b; Morales *et al.*, 2009; Lorenzen *et al.*, 2009; Wilson and Militzer, 2010; Morales *et al.*, 2013], with consideration of a dilute core in section 2.3. We then describe the results of these models in terms of their calculated  $J_n$  (section 3.2) and heavy element mass and distribution (section 3.3). Finally, in section 4 we discuss these results in relation to the present state of measurements of, as well as theory for, the formation and evolution of Jupiter.

## 2. Materials and Methods

### 2.1. Barotropes

In this paper we consider interior density profiles in hydrostatic equilibrium,

$$\nabla P = \rho \nabla U, \quad (1)$$

where  $P$  is the pressure and  $\rho$  is the mass density. In order to find a consistent density profile, we use a barotrope  $P(\rho)$  corresponding to isentropic profiles constructed from various equations of state.

Most of the results presented are based on density functional theory molecular dynamics (DFT-MD) simulations of hydrogen-helium mixtures from Militzer [2013] and Militzer and Hubbard [2013, hereafter MH13]. For densities below those determined by the ab initio simulations ( $P < 5$  GPa), we use the Saumon *et al.* [1995] equation of state (SCvH), which has been used extensively in giant planet modeling. The benefits of this simulation technique lie in its ability to determine the behavior of mixture through the metallization transition and to directly calculate entropy for the estimation of adiabatic profiles. The barotropes are parameterized in terms of helium and heavy element mass fraction  $Y$  and  $Z$  and specific entropy  $S$  as a proxy for the adiabatic temperature profile; for additional details see supporting information S1.

For comparison, we consider models using the ab initio equations of state of hydrogen and helium calculated by Becker *et al.* [2013] (REOS3) with the procedure for estimating the entropy described by Miguel *et al.* [2016]. Finally, we also consider models using the SCvH EOS through the entire pressure range of the planet. Although the SCvH EOS does not fit the most recent data from high-pressure shockwave experiments [Hubbard and Militzer, 2016; Miguel *et al.*, 2016], it is useful for comparison since it has been used to constrain Jupiter models in the past [e.g., Saumon and Guillot, 2004].

Different equations of state affect model outcomes in part by placing constraints on the allowable abundance and distribution of heavy elements. The DFT-MD isentrope consistent with the *Galileo* probe measurements has higher densities and a less steep isentropic temperature profile than SCvH in the vicinity of the metallization transition [Militzer, 2013; Militzer *et al.*, 2016]. The H-Reos equation of state has a similar shape to the  $T(P)$  profile but has an offset in temperature of several hundred thousands through much of the molecular envelope [Nettelmann *et al.*, 2012; Hubbard and Militzer, 2016; Miguel *et al.*, 2016].

DFT-MD simulation is the best technique at present for determining densities of hydrogen-helium mixtures over most of conditions in a giant planet ( $P > 5$  GPa). There is, however, a poorly characterized uncertainty in density for DFT-MD calculations. Shockwave experiments are consistent with DFT but can only test their accuracy to at best  $\sim 6\%$  [Knudson *et al.*, 2004; Brygoo *et al.*, 2015]. Moreover, there is a necessary extrapolation between  $\sim 5$  GPa, where the simulations become too computationally expensive [Militzer, 2013; Militzer and Hubbard, 2013] and  $\sim 10$  bar where the deepest temperature measurements from the *Galileo* probe were obtained [Seiff *et al.*, 1997]. We consider perturbations to the MH13 equation of state in the form of an entropy jump,  $\Delta S$ , at a prescribed pressure in the outer, molecular envelope; increases of  $S$  from 7.07 up to 7.30 (with  $S$  in units of Boltzmann constant per electron) are considered. These perturbations test the effect of a density

decrease through the entire envelope ( $P = 0.01$  GPa), at the switch from SCvH to DFT (5.0 GPa), and near the onset of the metalization transition (50.0 GPa).

Gravitational moments for the models are calculated using the nonperturbative concentric Maclaurin spheroid method [Hubbard, 2012, 2013; Hubbard and Militzer, 2016; Wahl et al., 2017]; see supporting information section S2 for additional details.

## 2.2. Model Assumptions

One of the most significant structural features of Jupiter's interior arises from a pressure-induced immiscibility of hydrogen and helium, which allows for rain out of helium from the planet's exterior to interior [Stevenson and Salpeter, 1977a, 1977b]. Ab initio simulations [Morales et al., 2009; Lorenzen et al., 2009; Wilson and Militzer, 2010; Morales et al., 2013] predict that the onset of this immiscibility occurs around  $\sim 100$  GPa, over a similar pressure range as the molecular to metallic transition in hydrogen. At higher pressures, the miscibility gap closure temperature remains nearly constant with pressure, such that in the deep interior temperatures are sufficient for helium to become miscible again.

The MH13 adiabats cross the Morales et al. [2013] phase diagram such that helium rain out occurs between  $\sim 100$  and 300 GPa [Militzer et al., 2016]. This is consistent with the subsolar  $Y$  measurement made by the *Galileo* entry probe [von Zahn et al., 1998]. The REOS3 adiabats are significantly warmer and require adjustments to the phase diagram in order to explain the observations [Nettelmann et al., 2015]. Although the detailed physics involved with the formation and growth of a helium rain layer is poorly understood [Fortney and Nettelmann, 2010], the existence of a helium rain layer has a number of important consequences for the thermal and compositional structure of the planet.

We calculate the abundance of helium in both the upper helium-poor (molecular hydrogen) region and lower helium-rich (metallic hydrogen) region by enforcing a helium to hydrogen ratio that is globally protosolar. We also allow for a compositional gradient of heavy elements across the layer with a mass mixing ratio that changes from  $Z_1$  in the lower layer to  $Z_2$  in the upper layer.

## 2.3. Dilute Core

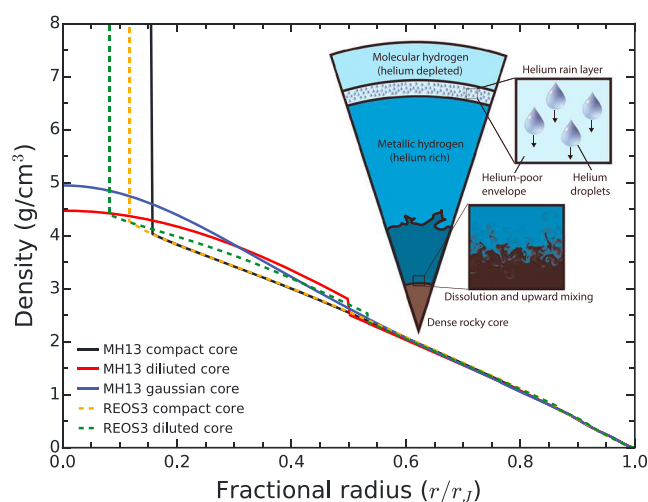
The thermodynamic stability of various material phases in giant planet interiors has been assessed using DFT-MD calculations [Wilson and Militzer, 2012a, 2012b; Wahl et al., 2013; Gonzalez-Cataldo et al., 2014]. These calculations suggest that at the conditions at the center of Jupiter, all likely abundant dense materials will dissolve into the metallic hydrogen-helium envelope. Thus, a dense central core of Jupiter is expected to be presently eroded or eroding. However, the redistribution of heavy elements amounts to a large gravitational energy cost and the efficiency of that erosion is difficult to assess [see Guillot et al., 2004]. It was recently shown by Vazan et al. [2016] that redistribution of heavy elements by convection is possible, unless the initial composition gradient is very steep. Some formation models suggest that a gradual distribution of heavy elements is an expected outcome, following the deposition of planetesimals in the gaseous envelope [Lozovsky et al., 2017]. The formation of a compositional gradient could lead to double-diffusive convection [Chabrier and Baraffe, 2007; Leconte and Chabrier, 2013] in Jupiter's deep interior, which could lead to a slow redistribution of heavy elements, even on planetary evolution timescales.

In a selection of the models presented here, we consider Jupiter's "core" to be a region of the planet in which  $Z$  is enriched by a constant factor compared to the envelope region exterior to it. This means that the model core is a diffuse region composed largely of the hydrogen-helium mixture. In fact, this configuration is not very different from the internal structure derived by Lozovsky et al. [2017] for proto-Jupiter. Given the current uncertainty in the evolution of a dilute core, we consider models with core in various degrees of expansion,  $0.15 < r/r_j < 0.6$ . In a few models, we also test the importance of the particular shape of the dilute core profile by considering a core with a Gaussian  $Z$  profile instead. Figure 1 demonstrates the density profiles resulting from these different assumptions about the distribution of core heavy elements.

## 3. Results

### 3.1. Comparison to Juno

The even zonal moments observed by *Juno* after the first two perijoves [Folkner et al., 2017] are broadly consistent with the less precise predictions of Campbell and Synnott [1985] and Jacobson [2003] but inconsistent with the more recent JUP310 solution [Jacobson, 2013]. Table 1 compares these observations with a few representative models. Although the solid-body (static) contribution dominates this low-order, even part of



**Figure 1.** Density profiles of representative models. Solid lines denote models using MH13, while dashed use REOS3. In black is a model with  $S$ ,  $Y$ , and  $Z$  matching that measured by the *Galileo* entry probe and a core with constant enrichment of heavy elements inside  $r/r_J = 0.15$ . In red (Model D)  $Z = 0.007$  in the molecular envelope and constant  $Z$ -enriched, dilute core expanded to  $r/r_J \sim 0.50$  to fit the  $J_4$  observed by *Juno*. In blue (Model E) with  $Z = 0.007$  also fitting  $J_4$  with Gaussian  $Z$  profile. In orange (Model R) and green (Model S) are profiles for the REOS3 models fitting  $J_4$  with a compact and dilute core, respectively. (Inset) Schematic diagram showing the approximate location of the helium rain layer and dilute core.

the gravity spectrum [Hubbard, 1999], a small dynamical contribution above *Juno*'s expected sensitivity must be considered [Kaspi et al., 2010]. For sufficiently deep flows, these contributions could be many times larger than *Juno*'s formal uncertainties for  $J_n$  [Kaspi et al., 2017] and thus represent the conservative estimate of uncertainty for the purpose of constraining the interior structure. Thus, ongoing gravity measurements by *Juno*, particularly of odd and high order, even  $J_n$ , will continue to improve our understanding of Jupiter's deep interior [Kaspi, 2013]. Marked in yellow in Figure 2 is the possible uncertainty considering a wide range of possible flows, and finding a corresponding density distribution assuming the large-scale flows is leading-order geostrophic [Kaspi et al., 2009]. The progressively smaller ellipses show how this uncertainty is reduced when the depth of the flow is restricted 10,000, 3000, and 1000 km, respectively. The relatively small range in our models  $J_6$  and  $J_8$  com-

pared to these uncertainties suggests that flows in Jupiter are shallower than the most extreme cases considered by Kaspi et al. [2017].

### 3.2. Model Trends

It is evident that the  $J_n$  observed by *Juno* are not consistent with the "preferred" model put forward by Hubbard and Militzer [2016], even considering differential rotation. Nonetheless, we begin with a similar model (Model A in Table 1) since it is illustrative of the features of the model using the MH13 equation of state with reasonable pre-*Juno* estimates for model parameters. A detailed description of the reference model is included in the supporting information section S3.

In order to increase  $J_4$  for a given planetary radius and  $J_2$ , one must either increase the density below the 100 GPa pressure level or conversely decrease the density above that level [Guillot, 1999, Figure 5]. We explore two possibilities: either we raise the density in the metallic region by expanding the central core or we consider the possibility of an increased entropy in the molecular region.

Figure 2 shows the effect of increasing the radius of the dilute core on  $J_4$  and  $J_6$ . Starting with the MH13 reference model with  $r/r_J = 0.15$  (Model A), the core radius is increased incrementally to  $r/r_J \sim 0.4$ , above which the model becomes unable to fit  $J_2$ . Therefore, considering an extended core shifts the higher-order moments toward the *Juno* values, but is unable to reproduce  $J_4$ , even considering a large dynamical contribution to  $J_n$ . Supporting information Figure S1 shows a similar trend for  $J_8$ , although the relative change in  $J_8$  with model parameters compared to the observed value is less significant than for  $J_4$  and  $J_6$ .

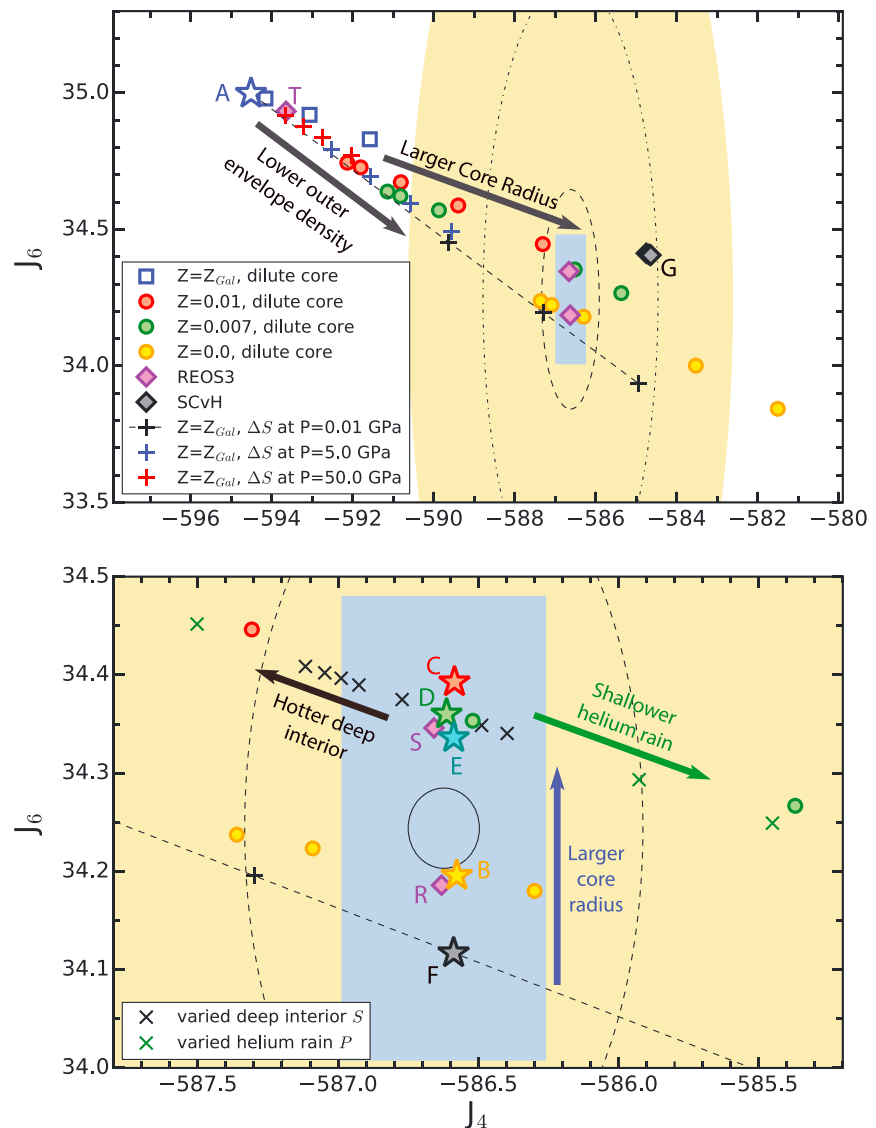
Precisely matching *Juno*'s value for  $J_4$  with the MH13-based models presented here requires lower densities than the reference model through at least a portion of the outer, molecular envelope. In the absence of additional constraints, this can be accomplished by lowering  $Y$  or  $Z$  or by increasing  $S$  (and consequently the temperature). In Figure 2 this manifests itself as a nearly linear trend in  $J_4$  and  $J_6$  (black plus symbols), below which there are no calculated points. This trend also improves the agreement of  $J_4$  and  $J_6$  with *Juno* measurements but with a steeper slope in  $J_6/J_4$  than that from the dilute core. For  $\Delta S \sim 0.14$  applied at  $P = 0.01$  GPa, a model with this perturbed equation of state can match the observed  $J_4$ , with a mismatch in  $J_6$  of  $\sim 0.1 \times 10^{-6}$  below the observed value (Model F). When the  $\Delta S$  perturbation is applied at higher pressures ( $P = 5.0$  and 50.0 GPa), a larger  $\Delta S$  is needed to produce the same change in  $J_4$ .

**Table 1.** Comparison of Selected Models to Observed Gravitational Moments<sup>a</sup>

	Model Description <sup>b</sup>	$Z_1^c$	$Z_2$	$J_2$	$J_4$	$J_6$	$J_8$	$J_{10}$	$C/Ma^2$	$r_{core}/r_J$	$M_{core}$	$M_{Z,env}$	$M_{Z,total}$	$Z_{global}$
<i>Juno</i> observed <sup>d</sup>														
			14,696.514	-586.623	34.244	-2.502								
				±0.272	±0.363	±0.236	±0.311							
A	MH13, $Z_{Gal}$ , compact core	0.0169	0.0298	14,696.641	-594.511	34.998	-2.533	0.209	0.26391	0.150	13.2	10.5	23.6	0.0744
B	MH13, dilute core	0.0000	0.0451	14,696.641	-586.577	34.196	-2.457	0.202	0.26400	0.270	10.4	13.9	24.2	0.0762
C	MH13, dilute core	0.0100	0.0114	14,696.467	-586.613	34.360	-2.481	0.205	0.26396	0.498	18.5	7.3	25.8	0.0812
D	MH13, dilute core	0.0071	0.0199	14,696.641	-586.585	34.392	-2.486	0.205	0.26396	0.530	21.3	5.1	26.4	0.0831
E	MH13, Gaussian core	0.0071	0.0087	14,696.467	-586.588	34.336	-2.479	0.204	0.26397	—	23.5	3.3	26.8	0.0843
F	Perturbed MH13, compact core	0.0169	0.0526	14,696.466	-586.588	34.117	-2.444	0.200	0.26400	0.150	9.3	15.9	25.1	0.0791
G	SCvH, compact core	0.0820	0.0916	14,696.641	-587.437	34.699	-2.541	0.212	0.26393	0.150	1.5	32.7	34.2	0.1076
R	REOS3, compact core	0.0131	0.1516	14,696.594	-586.631	34.186	-2.457	0.202	0.26443	0.110	6.21	40.0	46.2	0.1454
S	REOS3, dilute core	0.0209	0.0909	14,696.755	-586.658	34.346	-2.480	0.204	0.26442	0.533	19.2	14.5	33.7	0.1061
T	REOS3, compact core, low $J_4$	0.0293	0.0993	14,696.381	-593.646	34.933	-2.529	0.209	0.26432	0.122	8.9	27.0	35.9	0.1129

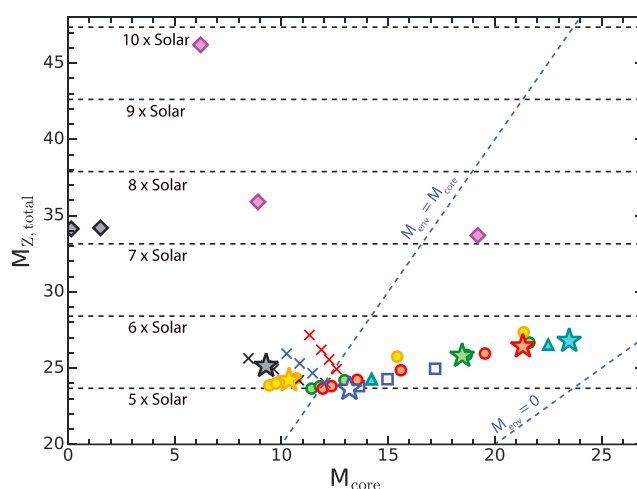
<sup>a</sup> $J_n$  in parts per million. Shaded rows are models that match the *Juno*-observed  $J_2$ – $J_8$  within the current uncertainty.<sup>b</sup>Equation of state used, dilute or compact core,  $Z_{Gal}$  denotes model with  $Z_1$  matching *Galileo* probe measurement.<sup>c</sup> $Z_1$  denotes the heavy element fraction in molecular envelope;  $Z_2$  denotes heavy element fraction in the metallic envelope but exterior to the core.<sup>d</sup>Folkner et al. [2017].





**Figure 2.** Zonal gravitational moments  $J_4$  and  $J_6$  for interior models matching the measured  $J_2$ . (top) The blue rectangle shows the uncertainty of the *Juno* measurements as of perijove 2 [Folkner et al., 2017]. The yellow ellipse shows the effective uncertainty in the static contribution due possible deep differential rotation [Kaspi et al., 2017] and with flow restricted to 10,000 km (dash dotted), 3000 km (dashed), and 1000 km (solid). The blue star is the reference (Model A, Table 1) with  $Z_{Gal}$  matching that measured by the *Galileo* entry probe and a core of  $r/r_j = 0.15$ . The blue squares show how these results change as a dilute core with a constant  $Z_1$  enrichment and core radius  $r$  increasing to the right. The green and red circles denote similar expanding core trends with lowered outer envelope heavy element fraction to  $Z_1 = 0.007$  and  $0.01$ , respectively. The plus symbols denote models which take perturb the MH13 EOS by introducing a jump in  $S$  at  $P = 0.01$  (black),  $P = 5.0$  (blue), and  $P = 50.0$  GPa (red), with  $Z_1$  decreasing to the right. Black diamonds show models using the SCvH EOS. (bottom) Models fitting the observed  $J_4$  yield larger  $J_6$  with increasing core radii. The stars denote Models B, C, D, E, and F in Table 1. Violet diamonds show models using the REOS3 EOS (Models R, S, and T). Black and green cross symbols show models starting with the green star (dilute core,  $Z_1 = 0.007$ ) and changing the  $S$  of the deep interior or the pressure of the onset of helium rain. Red, green, and cyan stars show models fitting the measured  $J_4$  with the radius of the dilute core. Black star shows model fitting  $J_4$  with the entropy jump magnitude  $\Delta S$ .

We also consider a number of models with both a decrease in the density of the outer, molecular layer and a dilute core. Here we present MH13 models where the core radius is increased for models with outer envelope  $Z = 0.010$ ,  $0.007$ , or  $0.0$ . Above  $Z \sim 0.010$  the models are unable to simultaneously match  $J_2$  and  $J_4$ . The models with  $Z = 0.010$  and  $Z = 0.007$  can both fit  $J_4$  but with a  $J_6 \sim 0.1 \times 10^{-6}$  above the observed value (Models C and D). These models also require extremely dilute cores with  $r/r_j \sim 0.5$  in order to match  $J_4$ . A more extreme model with no heavy elements ( $Z = 0$ ) included in the outer, molecular envelope (Model B) can simultaneously match



**Figure 3.** Mass of heavy elements in the core of the model versus the total heavy element mass in Jupiter predicted by the model. Symbols refer to identical models as in Figure 2. The stars denote models included in Table 1. Horizontal lines display the values of  $M_{Z, \text{total}}$  corresponding to 5–10 times solar abundance of heavy elements.

REOS3 adiabat, for a three-layer model with a compact core and when adding a dilute core, respectively. Because of the flexibility due to the larger  $Z$  values that are required to fit Jupiter's mean density, there is a wide range of solutions [Nettelmann et al., 2012; Miguel et al., 2016] with  $J_4$  values that can extend all the way from  $-599 \times 10^{-6}$  to  $-586 \times 10^{-6}$ , spanning the range of values of the MH13 solutions. Model T corresponds to a model calculated with the same  $\Delta Z$  discontinuity at the molecular-metallic transition as Model S but with a compact instead of dilute core. This shows that, as in the case of the MH13 EOS, with all other parameters fixed, a dilute core yields larger  $J_4$  values.

For both DFT-based equations of state, we find that heavy element abundances must increase in the planet's deep interior. The required  $\Delta Z$  across the helium rain layer is increased with the REOS3 equation of state and decreased by considering a dilute core. Regardless of the EOS used, including a diffuse core has a similar effect on  $J_6$ , increasing the value by a similar amount for similar degree of expansion, when compared to an analogous model with a compact core. Thus,  $J_6$  may prove to be a useful constraint in assessing the degree of expansion of Jupiter's core.

### 3.3. Predicted Core Mass

Figure 3 displays the total mass of heavy elements, along with the proportion of that mass in the dilute core. Models using MH13 with dilute cores, have core masses between 10 and 24  $M_{\oplus}$  (Earth masses), with gradual increase from 24 to 27  $M_{\oplus}$  for the total heavy elements in the planet. Of the models able to fit the observed  $J_4$ , those with heavy element contents closer to the *Galileo* value have more extended cores containing a greater mass of heavy elements.

The perturbation of the equation of state with an entropy jump has an opposite effect on the predicted core mass with respect to the dilute core, despite the similar effect on the calculated  $J_n$ . For increasingly large  $\Delta S$  perturbations, core mass decreases, to  $\sim 8 M_{\oplus}$ , while total heavy element mass increases. As this perturbation is shifted to higher pressures the change in core mass becomes less pronounced, for a given value of  $\Delta Z$ . In all the cases considered here, the MH13 equation of state predicts significantly larger core masses and lower total heavy element mass than the SCvH equation of state.

All of the models depicted in Figure 3 represent fairly conservative estimates of the heavy element mass. For any such model, there is a trade-off in densities that can be introduced where the deep interior is considered to be hotter (higher  $S$ ) and that density deficit is balanced by a higher value of  $Z$ . It is also possible that a dilute core would introduce a superadiabatic temperature profile, which would allow for a similar trade-off in densities and additional mass in the dilute core. Constraining this requires an evolutionary model to constrain the density and temperature gradients through the dilute core [Leconte and Chabrier, 2012, 2013] and has not

$J_4$  and  $J_6$  within the current uncertainty, with a less expansive core with  $r/r_j \sim 0.27$ . The dilute core using the Gaussian profile and an outer envelope  $Z = 0.007$  (Model E) has a very similar trend in  $J_4$ – $J_6$ , although it is shifted to slightly lower values of  $J_6$ .

There are a number of other model parameters which lead to similar, but less pronounced, trends than the dilute core. Starting with Model C, we test shifting the onset pressure for helium rain, between 50 and 200 GPa, and the entropy in the deep interior,  $S = 7.07$  to 7.30 (Figure 2 (bottom)). Both modifications exhibit a similar slope in  $J_4$ – $J_6$  to the models with different core radii but spanning a smaller range in  $J_4$  than for the dilute core trend.

The models using REOS3 have a significantly hotter adiabatic  $T$  profile than MH13. Models R and S in Tables 1 are two example solutions obtained with the



been considered here. Shifting the onset pressure of helium rain can shift the core mass by  $\sim 2 M_{\oplus}$  in either direction. If the majority of the heavy core material is denser rocky phase [Soubiran and Militzer, 2016], the corresponding smaller value of  $\rho_0/\rho_Z$  results in a simultaneous decrease in core mass and total  $Z$  of  $\sim 2-4 M_{\oplus}$ .

Using the REOS3, both models with a small, compact core of  $\sim 6 M_{\oplus}$  or a diluted core of  $\sim 19 M_{\oplus}$  are possible, along with a continuum of intermediate solutions. These models have a much larger total mass of heavy elements, 46 and  $34 M_{\oplus}$ , a direct consequence of the higher temperatures of that EOS [see Miguel *et al.*, 2016]. The enrichment in heavy elements over the solar value in the molecular envelope corresponds to about 1 for Model R and 1.4 for Model S, pointing to a water abundance close to the solar value in the atmosphere of the planet. In spite of the difference in total mass of heavy elements, the relationship between core mass and radius is similar for MH13 and REOS3.

In lieu of additional constraints we can likely bracket the core mass between 6 and  $25 M_{\oplus}$ , with larger masses corresponding to a more dilute profile of the core. These masses for the dilute core are broadly consistent with those required by the core collapse formation model Pollack *et al.* [1996], as well as models that account for the dissolution of planetesimals [Lozovsky *et al.*, 2017]. The mass of heavy elements in the envelope, and thus the total heavy element mass, is strongly affected by the equation of state, with MH13 predicting 5–6 times solar fraction of total heavy elements in Jupiter and REOS3 around 7–10 times solar fraction.

#### 4. Conclusion

After only two perijoves the *Juno* gravity science experiment has significantly improved the measurements of the low-order, even gravitational moments  $J_2-J_8$  [Folkner *et al.*, 2017]. The formal uncertainty on these measured  $J_n$  is already sufficiently small that they would be able to distinguish small differences between interior structure models, assuming that the contribution to these low-order moments arises primarily from the static interior density profile. Considering a wide range of possible dynamical contributions increases the effective uncertainty of the static  $J_2-J_8$  by orders of magnitude [Kaspi *et al.*, 2017]. It is expected that the dynamical contribution to  $J_n$  will be better constrained following future perijove encounters by the *Juno* spacecraft with measurements of odd and higher-order even  $J_n$  [Kaspi, 2013].

Even with this greater effective uncertainty, it is possible to rule out a portion of the models presented in this study, primarily on the basis of the observed  $J_4$ . The reference model, using a DFT-MD equation of state with direct calculation of entropy in tandem with a consistent hydrogen-helium phase diagram, is incompatible with a simple interior structure model constrained by composition and temperature from the *Galileo* entry probe.

Our models suggest that a dilute core, expanded through a region 0.3–0.5 times the planet's radius is helpful for fitting the observed  $J_n$ . Moreover, for a given  $J_4$  the degree to which the core is expanded affects  $J_6$  and  $J_8$  in a predictable, model-independent manner, such that further constraining  $J_6$  and  $J_8$  may allow one to determine whether Jupiter's gravity requires such a dilute core. Such a core might arise through erosion of an initially compact rock-ice core or through a differential rate of planetesimal accretion during growth, although both present theoretical challenges.

Using the REOS3 approach leads to a wider range of possibilities which include solutions with the standard three-layer model approach or assuming the presence of a dilute core. In any case, as for the MH13 solutions, the REOS3 solutions require the abundance of heavy elements to increase in the deep envelope. This indicates that Jupiter's envelope has not been completely mixed.

The dilute core models presented here are preliminary with few key assumptions, which may be relaxed with future work. The first is the simple adiabatic temperature profile through the deep interior, in lieu of more consistent profiles in  $T$  and  $Z$ . Second is the use of the ideal volume law, which does not necessarily remain a good assumption for the high  $Z$  in the planets core. Based on the range of models with different interiors  $S$  and  $Z$ , we expect more realistic treatments to have only a minor on calculated  $J_n$ , although changes in the predicted heavy element contents on the order of a few  $M_{\oplus}$  can be expected. In any case, these assumptions have a smaller effect on model predictions than the differences in EOS at present.

These results present a challenge for evolutionary modeling of Jupiter's deep interior [e.g., Vazan *et al.*, 2016; Mankovich *et al.*, 2016]. The physical processes involved with the formation and stability of a dilute core are not understood. It strongly depends on the formation process of the planet and the mixing at the early stages after

formation and also enters a hydrodynamical regime of double-diffusive convection where competing thermal and compositional gradients can result in inefficient mixing of material [Leconte and Chabrier, 2012; Mirouh et al., 2012]. The timescale for the formation and evolution of such features, especially on planetary length scales, is still poorly understood. In particular, it is not known whether there would be enough convective energy to expand  $10 M_{\oplus}$  or more of material to 0.3 to 0.5 times Jupiter's radii. It is also presently unknown whether it is plausible to expand the core to this degree without fully mixing the entire planet and without resorting to extremely fortuitous choices in parameters. Since Jovian planets are expected to go through periods of rapid cooling shortly after accretion [Fortney and Nettelmann, 2010], if they are mostly convective, it is likely that much of the evolution of a dilute core would have to occur early on in the planet's history when the convective energy is greatest. This presents a challenge for explaining interior models requiring a large  $\Delta Z$  across the helium rain layer, as such a layer would form after the period of most intense mixing.

In our preliminary models, those able to fit  $J_4$  have lower densities in portions of the outer molecular envelope than MH13. This is achieved through modifying abundances of helium and heavy elements to be lower than those measured by the *Galileo* entry probe or invoking a hotter nonadiabatic temperature profile. Some formation scenarios [e.g., Mousis et al., 2012] can account for relatively low envelope  $H_2O$  content ( $\sim 2$  times solar), but our models would require even more extreme depletions for this to be explained by composition alone. Alternatively, there might be an overestimate of the density inherent to the DFT simulations of MH13 of the order of  $\sim 3\%$  for  $P < 100$ .

Interior models could, therefore, be improved through further theoretical and experimental studies of hydrogen-helium mixtures, particularly in constraining density in the pressure range below  $\sim 100$  GPa, where the models are most sensitive to changes in the equation of state. More complicated equation of state perturbations, including the onset and width of the metallization transition [Knudson and Desjarlais, 2017], may be worth considering in future modeling efforts. Similarly, the interior modeling effort will be aided by an independent measurement of atmospheric  $H_2O$  from *Juno*'s microwave radiometer instrument [Helled and Lunine, 2014].

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